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MICROWAVE ROTARY JOINTS FOR X-, C-, AND S-BANDS

by
Basil J. Nicholson

November 1965

Contract No. DA-01-021-AMC-11706(Z)
Battelle Memorial Institute
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505 King Avenue
Columbus, Ohio 43201

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Research Branch
Redstone Scientific Information Center
Research and Development Directorate
U. S. Army Missile Command
Redstone Arsenal, Alabama 35809

ABSTRACT

This report consists of an examination of post-1950 rotary joint designs for use at X-, C-, and S-bands. Among the topics discussed are single and multichannel rotary joints with coaxial line or rectangular waveguide inputs. Since the simplest waveguide rotary joints incorporate transitions from rectangular to circular waveguide or from rectangular waveguide to a coaxial line, calculations are included on the relative power-handling capabilities of circular waveguide, rectangular waveguide, and coaxial line when subject to the conditions necessary for proper functioning of a rotary joint.

A detailed examination is made of rectangular waveguide joints of the coaxial line, circular waveguide, coaxial mode convertor, and of the annular varieties. It is shown that, in the circular waveguide variety, either a circularly polarized H_{11} mode or an E_{01} mode can be used. Methods of avoiding undesirable performance due to resonances in the circular waveguide are discussed. Methods are described of using circular waveguide rotary joints for dual-channel applications.

Rotary joints, incorporating a section of coaxial line, are discussed; it is shown that, for "around-the-mast" applications, by employing special feeds to the coaxial section, coaxial-line dimensions can be increased without appreciably exciting higher, undesirable modes which could in theory propagate. A brief discussion is also made of purely-coaxial rotary joints.

The more complicated mode convertor and annular-rotary joint designs are described, and it is indicated that, like certain waveguide rotary joints incorporating a coaxial line section, their chief merit lies in their possibility of use for "around-the-mast" applications.

FOREWORD

This report, setting forth the current state-of-the-art as it applies to rotary joints for X-, C-, and S-band applications, was written at the request of Electromagnetics Laboratory, U. S. Army Missile Command, Huntsville, Alabama.

The sources of information used in preparing this report were primarily the open technical literature, the patent literature, and published DDC reports. During the course of this contract, catalogue literature from approximately 30 designers and manufacturers of rotary joints was examined, and visits were made to the more active companies in this field. Apart from providing useful perspective and opinion exchanges, these visits were advantageous in that further patent and DDC references were obtained which had not been discovered previously.

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Section I. INTRODUCTION

Until the advent of phased arrays and electronically steerable beams, it was necessary in a radar system that the antenna be capable of rotation, either through 360 degrees or through a smaller angle when sector scanning was required. It is normally desirable, from the point of view of convenience and ease in mechanical design, that the transmitting and receiving equipment be stationary and connected to the antenna through a rotary joint. In addition, the use of multipurpose antennas in systems for reconnaissance and other purposes has created a need for rotary joints which can handle a multiplicity of channels.

In this report, the present state-of-the-art in the field of microwave rotary joints is examined. Particular reference is given to X-, C-, and S-bands; but, where design techniques exist for other bands which apparently are capable of being scaled without difficulty to X-, C-, or S-bands, these are noted.

Useful background information can be found in the book Fields and Waves in Modern Radio,[1] and in the following volumes of the Radiation Laboratory Series from Massachusetts Institute of Technology.

Volume 8

Section 6.21 Series Branches in Coaxial Lines
8.1 - 8.7 Radial Transmission Lines
10.1 Mode Transformers
10.12 Resonance in a Closed Circular Guide

Volume 9

Section 2.17 Series Branch and Choke or Capacity Coupling
6.3 - 6.15 Transitions from Coaxial Line to Waveguide
6.20 - 6.25 Transitions Involving a Change in Waveguide Mode

Volume 10

Section 2.7 Radial Waveguides

In a rotary joint, one is faced with the situation where a mechanical break must be made to allow relative motion between the rotating and stationary members of the joint. In order that continuity be maintained across the break, resort is usually made to a series half-wave choke

or to sliding conducting contacts. In the half-wave choke, the mechanical break is accomplished in the quarter-wave plane where the currents are zero. Under these conditions, no leakage of microwave energy occurs, and no mismatches are introduced into the line. Sliding contacts have also been used to maintain continuity across stationary and rotating parts; these have been either a coin silver--silver-graphite combination--or more simply, the spring-contact type. Mismatches can be kept small, but sliding contacts generate much more electrical noise than half-wave chokes and, for many applications, eliminates them from consideration. However, since a half-wave choke is necessarily a resonant structure, its useful bandwidth will be limited. This limitation is not possessed by sliding contacts.

Rotary joints are classified as either waveguide or coaxial type, depending on the nature of input and output feeds to the joint. Since the power must be transmitted in a circularly symmetrical mode across the rotor-stator interface, it is necessary in rotary joints with rectangular waveguide feeds to make a transition to either a coaxial line or a circular waveguide and locate the physical break. Although a dual-channel rotary joint, to be described later, has a coaxial line feeding one channel into circular waveguide, this is unusual. Power is normally transmitted across the rotorstator interface in a coaxial mode with coaxial inputs and outputs.

Since the cross section of any waveguide at the rotor-stator interface should possess circular symmetry, it follows that the only two suitable forms are the coaxial line and the hollow-circular waveguide. Furthermore, the field configurations of the mode propagating across the rotor-stator interface should also possess circular symmetry. Where rectangular waveguides are used as input and output feeds, a transition to coaxial line or circular waveguide from the rectangular guide is an important part of the rotary joint. To be satisfactory, this transition should effect two things:

1) Launch the desired symmetrical mode of propagation in the coaxial line or circular guide with a minimum of unwanted modes.
2) Provide minimal impedance mismatch over the frequency band of interest.

There is no difficulty in launching a symmetrical mode in a coaxial line since the fundamental mode is symmetrical. However, the fundamental H_{11} mode in circular waveguide is polar; the lowest symmetrical mode is E_{01}, and the tube diameter must be large enough to support this mode. A certain amount of H_{11} mode will inevitably be present in

circular waveguide and, when appreciable amounts are present, problems of resonance and large wow (the ratio of maximum to mininum voltage-standing-wave ratio (VSWR) observed during one complete rotation of a rotary joint) occur. Therefore, the transition should launch the E_{01} mode in circular guide with a minimum of H_{11} mode; the residual H_{11} power can then be attenuated by various techniques as described below.

Moding problems of this type do not arise with coaxial lines, providing the cross-sectional dimensions of the line are not great enough to permit the propagation of higher modes.

It is appropriate at this point to examine how coaxial lines and circular waveguide compare with rectangular waveguide in power-handling capabilities. Assuming that the coaxial line is dimensioned to pass the maximum power for a given field strength at the surface of the center conductor when the sum of a and b is kept constant,

$$b/a = 2.09, \qquad (1)$$

where b = inner diameter of outer conductor
a = outer diameter of center conductor (1),
then the relative power-handling capabilities of coaxial line compared with rectangular waveguide can be assessed in the following manner. It is assumed that the maximum allowable electric field strength is 2.5 millivolt per meter, a value close to the breakdown value for air at a pressure of 1 bar.* If d is the inside dimension of the broad face in rectangular guide, the cutoff wavelength λ_c for the fundamental mode H_{10} is $\lambda_c = 2d$. The cutoff wavelength for the next higher mode, H_{20}, is given by $\lambda = d$. Therefore, one can consider a rectangular waveguide as operable at wavelengths between $0.5\ \lambda_c$ and $0.9\ \lambda_c$. Thus, if one wishes to operate a waveguide-coaxial line transition at wavelengths down to $\lambda = d = 0.5\ \lambda_c$. one can postulate at this wavelength that the next higher mode is also possible in the coaxial line.

Therefore,
$$\lambda = d = \frac{\pi\ (a + b)}{1.015}. \qquad (2)$$

*1 bar = 10^5 newtons/square meter (14.4 psi). The Standard Atmosphere (760 torr) is by definition 1.01325 bar.

Therefore,

$$a + b = \frac{1.015}{\pi} d. \tag{3}$$

Since $b/a = 2.09$,

$$a = 0.104d \tag{4}$$
$$b = 0.217d. \tag{5}$$

However, if one does not wish to operate at wavelengths less than $0.6\ \lambda_c$, b can be increased by 20 percent. The corresponding increase in power-handling capability is 44 percent. Therefore,

$$a = 0.125d \tag{6}$$
$$b = 0.26d. \tag{7}$$

Using these latter values, the power-handling capabilities of air-filled coaxial lines, which correspond by the above equations to various rectangular waveguides, have been calculated and plotted in Figure 1.

For coaxial line, the power P is given by

$$P = \frac{E^2 a^2}{120} \ln \frac{b}{a}, \tag{8}$$

where E = maximum electrical field strength. For comparison, the power-handling capabilities of rectangular and circular (E_{01} mode) waveguides are also plotted in Figure 1. For rectangular guide (H_{10} mode),

$$P = 6.63 \times 10^{-4}\ E^2\ dh \sqrt{1 - (\lambda/\lambda_c)^2}, \tag{9}$$

where h = inside dimension of narrow face.

Values of P are plotted for wavelengths between $0.5\ \lambda_c$ and $0.9\ \lambda_c$.

For the circular guide (E_{01} mode),

$$P = 2.825 \times 10^{-4}\ D^2 E^2\ (\lambda_c/\lambda)^2 \sqrt{1 - (\lambda/\lambda_c)^2}, \tag{10}$$

and $\lambda_c = 1.305$ D, where D = inside diameter of the circular waveguide.

The circular waveguide is not operated at wavelengths below 1.03 D ($\lambda = 0.785\ \lambda_c$) since the next higher mode, H_{21}, can then be propagated.

Therefore, consideration of the E_{01} mode was limited to wavelengths between $0.8\ \lambda_c$ and $0.9\ \lambda_c$. These values are illustrated in Figure 1 for several values of D. The center frequency of each useful band corresponds to a wavelength of $0.85\ \lambda_c$.

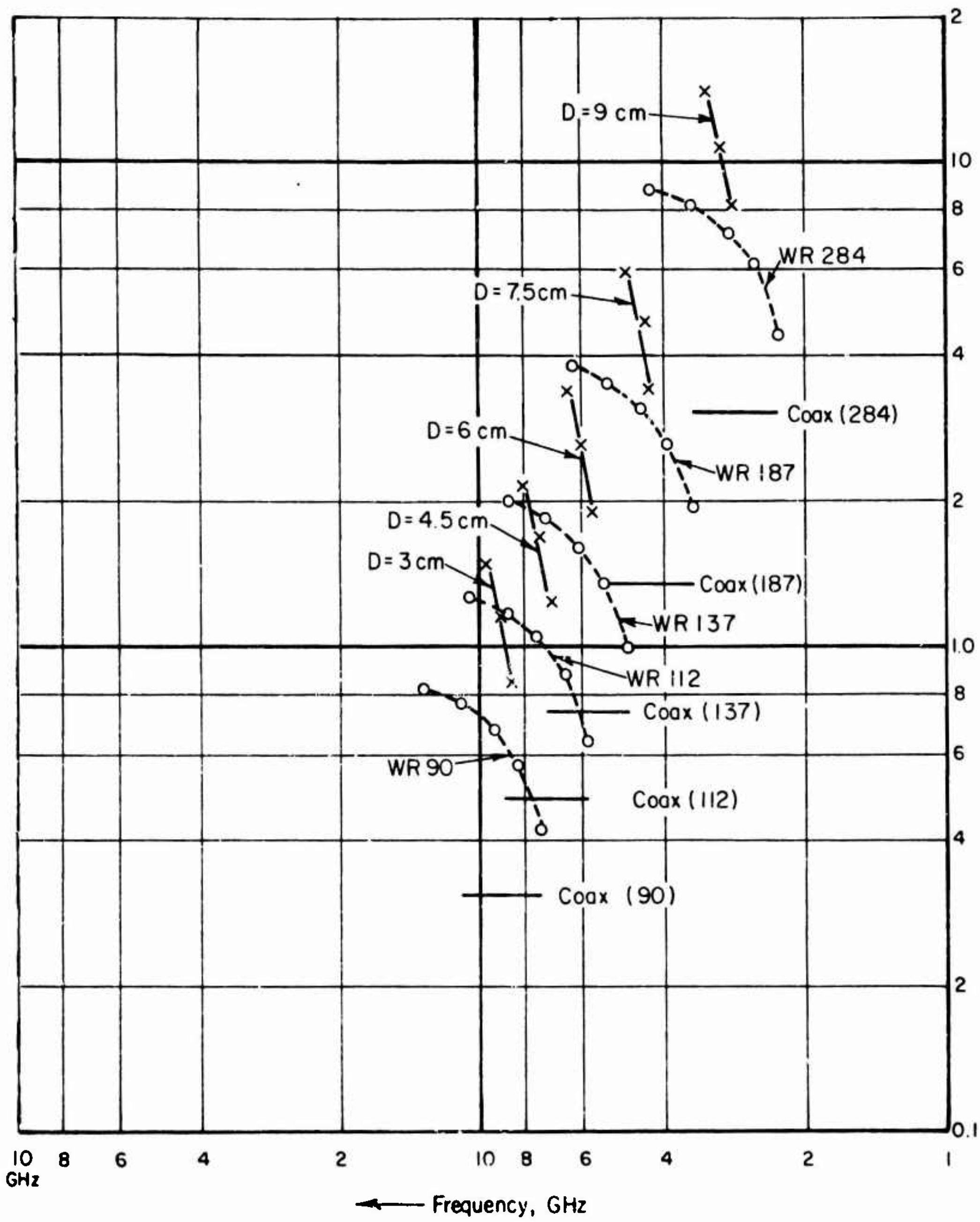
It is clear that the coaxial line has lower power-handling capabilities than rectangular waveguide by factors varying from 2.5 to 1.4. One could increase the cross-sectional dimensions of the coaxial line to diminish the differences, but only at the expense of not being able to use higher frequencies without incurring the risk of propagating higher modes in the coaxial line.

On the other hand, the circular waveguide passes higher powers than the corresponding rectangular waveguide by factors varying from 2.2 to 1.5. It possesses a smaller usable frequency band than rectangular guide.

There is a certain amount of ambiguity in the field concerning the meaning of the terms wow and bandwidth.

In this report, wow (as previously defined) will be understood as the ratio of maximum to minimum VSWR observed during one complete rotation of a rotary joint. Under certain conditions, the insertion loss of a rotary joint will vary as the joint is rotated. While some workers in the field have defined wow in terms of the variation in insertion loss, this is preferably spelled out as a variation of insertion loss with rotation.

Bandwidth is defined just as the bandwidth of a resonant circuit; that is, if a component possesses acceptable properties within a frequency band extending from $f_o - \Delta f$ to $f_o + \Delta f$, the bandwidth is defined as $2\Delta f/f_o$. No reference to the width of an arbitrary microwave band such as C-band is involved. For example, a rotary joint working from 9 to 11 GHz (gigahertz) has a bandwidth of 20 percent. This can be alternatively expressed as ± 10 percent bandwidth.



Note: Coax (90) Refers to Coaxial Line of Dimensions Related to WR 90 Waveguide by Equations (6) and (7).

Figure 1. Variation of Power Corresponding to a Maximum Electric Field Strength of 2.5 MV/m in Rectangular, Circular and Coaxial Line Waveguides as a Function of Frequency

Section II. DISCUSSION OF ROTARY JOINTS

An examination has been made of microwave rotary joints useful for X-, C-, and S-band applications. Their electrical performance has been of primary interest; no consideration has been given to mechanical and pressurizing aspects. Electrical parameters to which attention has been given include bandwidth, wow, insertion loss, power-handling capability, and variation of electrical length as the joint rotates. Single-channel joints can be either of the purely-coaxial type or have rectangular-waveguide input and output. The latter represents joints employing a coaxial line or circular waveguide at the rotor-stator interface, mode-convertor rotary joints in which a simulated H_{01} coaxial mode is propagated across the rotor-stator interface and a variety of annular designs which incorporate waveguide ring sections such that the ring output feed can take up any position on the circumference of a circle.

Waveguide rotary joints, incorporating circular waveguide at the rotor-stator interface, operate using either the symmetrical E_{01} mode or a circularly polarized H_{11} mode. Rotary joints employing circular polarization and annular rotary joints have a variable electrical length as the joint rotates. Resonance problems are encountered both with annular rotary joints and with rotary joints employing circular waveguide propagating the E_{01} or H_{11} mode. It appears that, for circular (E_{01} mode) rotary joints, these problems can be solved; however, since resonance problems are not encountered in waveguide rotary joints having a coaxial line at the rotor-stator interface, this type of rotary joint is widely used for single-channel applications.

Circular waveguide can be used for dual-channel applications; isolation between the two channels is achieved either by propagating two different modes (E_{01} and H_{01}) or by propagating two circularly polarized H_{11} waves of opposite sign. A dual-channel joint is also possible where one channel must carry a frequency three times that of the other channel; the low-frequency input feed is coaxial and the other input feed is in waveguide. Both channels pass along the same coaxial line across the rotor-stator interface. Separation between the channels depends on the change with frequency of choke impedances.

In waveguide-coaxial line rotary joints, there are possibilities for multichannel operation if the coaxial center conductor passes right across the rectangular waveguide as, for instance, in the doorknob type of transition. If the inner conductor is hollow, this can function as the outer conductor of a second channel, and this process can be repeated

perhaps a few times more. The same principle applies to multichannel purely-coaxial rotary joints. This process of cascading channels cannot be repeated indefinitely. Apart from physical size problems, propagation of higher modes must be avoided and the power-handling capability of the inner channels decreases.

A variety of rotary joints exists,which is termed "around-the-mast" by virtue of a large central hole through which feeds to other rotary joints may pass. These joints can be stacked one above the other (as many as 15 have been described) to provide a multichannel rotary joint with perhaps all joints being capable of handling powers in the megawatt range.

Annular waveguide rotary joints belong to this category of "around-the-mast" rotary joints. Two other important types of rotary joints are the pancake joint and its variant, the "neutral-plane-feed" joint. These consist of a coaxial cavity large enough to accommodate the central hole, but also large enough to propagate higher modes in addition to the fundamental mode. The propagation of higher modes is avoided by feeding the cavity at four coplanar symmetrical points with a binary stripline feed.

Another variation to this approach is the coaxial-sleeve rotary joint in which the central hole is sufficiently small that higher modes are not possible in the coaxial cavity. It, therefore, is fed at one point only. The smaller coaxial dimensions lead to greatly reduced power-handling properties, and this type of joint is more useful for receiving applications.

The properties of various multichannel rotary joints are summarized in the table on the following page.

1. Waveguide Rotary Joints Using the E_{01} Mode in Circular Waveguide

A rotary joint can be operated,using circular waveguide,if the power is transmitted in an axially symmetric mode. The lowest such mode is the E_{01} mode (λ_c = 1.305 D, where D = inside diameter of the waveguide); the next higher mode is the H_{21} (λ_c = 1.03 D). However, the E_{01} mode is not the lowest mode possible in circular waveguide, this being the nonsymmetrical H_{11} mode (λ_c = 1.705 D). Consequently, it is necessary for the rectangular-to-circular waveguide transition to excite the E_{01} mode with a minimum of the H_{11} mode in order to achieve minimum values of wow. Such power,transmitted in the H_{11} mode, can then be attenuated to acceptable levels by methods discussed below.

Characteristics of Rotary Joints for Multichannel Applications

Type of Joint	Approximate Peak Power Handling Capacity (S-band, unpressurized joint)	Approximate Bandwidth (percent)	Relative Cost	Remarks
Doorknob transition	2 MW	7 to 8	Least expensive	Handles relatively high-power in one channel. Can handle more than one channel if low-impedance line is used, but impedance matching is difficult
Double wave-guide transition	7 MW but feed must be pressurized	15	1-1/2 times the cost of the doorknob-transition joint	Limited by H_{21} coaxial mode. Capable of very high power
Coaxial sleeve	100 kW	10 to 12	Inexpensive for low power	Generally used for receiver channels
Pancake	2-1/2 MW (pressu- limited by strip-feed	12 to 15	Several times that of coaxial sleeve becomes rather expen-sive for higher power	Extremely stackable Generally used for receiver channels
Neutral plane feed system	Same as pancake	30	Slightly less than pancake	Similar to pancake joint, but feed system acts as a coupling loop
H_{01}-coaxial (wave-guide mode con-vertor)	15 MW but feed must be pressurized	30	Ultimately comparable to pancake joint	Extreme power joint lends itself readily to precision casting
Annular waveguide	1 MW	Narrow, due to resonance effects	Uncertain; not inexpensive	Electrical length varies on rotation

The proper design of the transition from rectangular-to-circular waveguide plays an important role in the acceptable functioning of the joint. An in-line transition tends to excite the H_{11} mode, and consequently, all designs described consist of the rectangular waveguide "looking" into the side of the circular waveguide. Thus, the guided waves change direction by 90 degrees. There are several variations on this theme. For instance, the transition may incorporate a half-wave stub and a matching diaphragm as shown in Figure 2. The optimum diameter for the stub is smaller than the tube diameter. A VSWR less than 1. 15 is obtained over a bandwidth of about five percent.

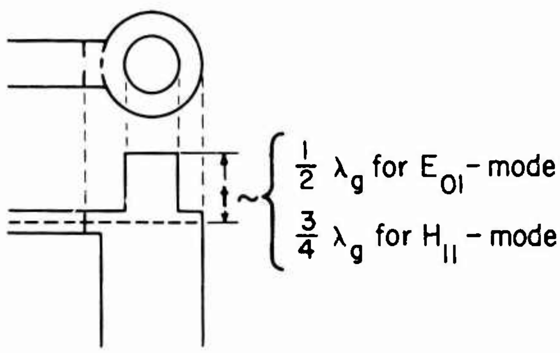


Figure 2. Stub-Matched Rectangular-to-Circular Waveguide Transition

Another design shown in Figure 3 consists of a transformer section at the end of the circular waveguide, the rectangular guide being fed into the transformer section. An optimum value of diameter d exists for best match. There is a capacitive diaphragm in the circular waveguide and an inductive iris in the rectangular waveguide. A VSWR less than 1. 10 is obtained over a 12-percent bandwidth.

Similar designs have been described in the literature[2,3,4,5] which essentially represent variations of the designs described. In the patent references, quantitative electrical performance data are almost invariably absent, preventing meaningful comparisons.

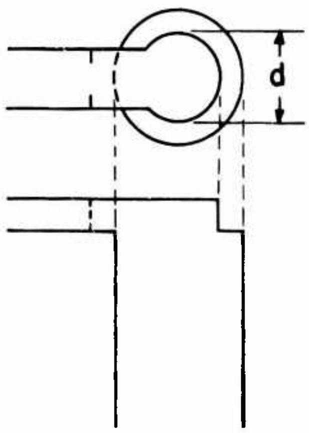


Figure 3. Transformer-Matched Rectangular-to-Circular Waveguide Transition

Having described the transition from rectangular to circular, the length of the circular waveguide before transformation back to rectangular waveguide must now be considered. When the equivalent electrical length of the circular waveguide for the H_{11} mode is an integral number of half-guide wavelengths long, undesirable resonance effects are set up which increase greatly the amount of H_{11} power present in the guide and, in consequence, wow is increased. Furthermore, as the joint is rotated through 360 degrees, the equivalent electrical length of the circular waveguide will vary for the H_{11} mode. Thus, resonance might only exist over limited angular sectors of rotation. At adjacent frequencies, resonance would occur at somewhat different angular positions on rotation. For narrow band applications, such a joint can be operated at frequencies away from resonant frequencies; for lengths of circular waveguide several multiples of half the guide wavelength (for H_{11} mode) the useful frequency band between frequencies at which resonant effects are troublesome is going to be rather small. It is important, therefore, to keep the circular waveguide as short as possible, consistent with other existing factors in order to increase the usable range between resonance frequencies as much as possible.

Satisfactory methods exist for supressing H_{11} power levels to the point where troublesome resonance effects do not appear. These are the resonant ring, the resonant stub, and the coupling slot methods. Of these, the resonant ring method seems to be the most widely used.

a. Resonant Ring Method of H_{11} Mode Suppression

In brief, a metallic ring inserted into circular waveguide offers a small capacitative mismatch to the E_{01} mode but presents a parallel tuned circuit to the H_{11} mode. Its resonant frequency is determined by its dimensions; for very thin rings, the resonant wavelength approximates the ring circumference, while, for thicker rings, the resonant wavelength assumes smaller values.

When insufficient H_{11} mode attenuation is afforded by one ring over the frequency band of interest, two or more such rings may be used. These are preferably spaced separately from each other by odd multiples of one-fourth the waveguide wavelength (λ_g) for improved match over the widest possible frequency band.

It is important that the resonant ring be circularly symmetrical for uniform H_{11} suppression as the joint rotates; thus the necessity arises for supporting it in a dielectric. Some designs have been described by Grantham[6] whereby the ring is supported by metal arms, but, in these instances, the attenuation afforded to the H_{11} mode varies depending on the relative orientation of the polarization plane and the metal support rings. In certain angular orientations, the attenuation effects on the H_{11} mode may then be insufficient and values of wow are too large. Therefore, the superior design is one in which the ring is completely symmetrical and held symmetrically in a dielectric support. Kurz[2] used polystyrene since this can be fastened to the waveguide walls by an epoxy cement. However, there exists a danger that, when large amounts of power are to be handled, the polystyrene might soften and distort since its softening point is around 80°to 90° C. Teflon does not suffer from this disadvantage and has excellent dielectric properties in the microwave region; however, it has not been used for this application, presumably because of the difficulties in cementing it firmly to the waveguide wall.

It has been reported[6] that voltage breakdown problems are commonly encountered with H_{11} resonant rings. While a polished ring with rounded edges can handle about 400 kilowatts at X-band, without pressurizing, a rough ring surface or small foreign particles on the ring can reduce the power that can be safely handled by a factor of 2. However, no

breakdown problems were mentioned by Kurz[2], so presumably, by giving sufficient care to ring preparation, they need not be a problem in handling high power.

b. Resonant Stub Method of H_{11} Mode Suppression

A second method of H_{11} mode suppression uses a stub extension of the circular guide (Figure 2). This stub can be considered as a reactance in series with the input. For good E_{01} transformation, a low series reactance is required and ℓ should be made an even number of quarter wavelengths for this mode. A H_{11} resonant ring may then be placed in the stub at a quarter-guide wavelength for H_{11} from the entrance to the stub. Thus, the cavity will behave as a E_{01} half-wave stub and as a quarter-wave stub for the H_{11} mode.

One can avoid the use of a resonant ring in the stub by increasing the length of the cavity and varying its diameter so that it represents three-quarters of a waveguide wavelength for the H_{11} mode and half of a waveguide wavelength for the E_{01} mode. A bandwidth of about five percent is obtained. Cavity dimensions are critical; the inner surface should be preferably clean and polished. In fact, the cavity should be machined from a solid casting because a good match is not obtainable using soldered end-plugs. Even with these precautions, suppression of the H_{11} mode is not complete, and a rotary joint of this type has to be used clear of resonant frequencies.

c. Coupling Slot Method for H_{11} Mode Suppression

H_{11} resonances in the circular waveguide can be prevented if the H_{11} power is coupled out of the waveguide into absorbing loads. This can be accomplished by narrow longitudinal slots in the waveguide which couple to the H_{11} mode but not to the E_{01} mode. As any H_{11} wave can be resolved into two H_{11} waves with their polarizations at right angles, four slots at 90 degree intervals around the guide will couple to any H_{11} wave in the waveguide. These slots couple into a cylindrical cavity where the H_{11} power is absorbed in rings of resistive material. At X-band, the slots are about 2.5 centimeters long so that the unit is quite compact. It is usual to place an absorbing cavity of this type near each transition; but where the break in the waveguide is placed near one end, it is sufficient to use one cavity near the center of the guide. When a single cavity is used, more care in design and construction is necessary if all the H_{11} power is to be absorbed. When a long joint is required to operate over a broad band, the use of two cavities is recommended. Joints of this type have been made as long as 1 meter at X-band with bandwidths of 12 percent.[6]

Circular rotary joints which operate successfully have been described.[2,7] Kurz,[2] who employed three resonant rings and covered the band from 8.5 to 9.6 GHz, had no resonance problems unless only one ring was used. It was uncertain just how much power the rotary joint would handle; Kurz stated that no problems at 260 kilowatt were encountered at atmospheric pressure and with 1 bar over-pressure, a power in excess of 1 milliwatt was passed.

Resonance problems were present in the work reported by General Electric.[7] They reported that addition of one ring considerably decreased wow, but no additional improvement resulted on the addition of a second ring. They were able to keep wow, for a particular length of circular guide, down to tolerable (unstated) values over a 10-percent band but not over the desired 12-percent band such as Kurz used.

There were a number of design differences between the two approaches. Separate from the number of mode-filter rings used, Kurz used a larger rectangular guide; he supported his rings with polystyrene, whereas General Electric supported theirs with nylon threads. Both used a circular waveguide of internal diameter 3.03 centimeter; examination of Figure 1 will indicate that, at the center frequency, a waveguide of this size has the same power-carrying capacity as large X (WR 112) rectangular waveguide.

The General Electric ring had circular cross section (1-millimeter diameter), whereas Kurz's ring was elliptical (0.73 x 1.1 millimeter). Kurz's ring was of larger diameter (1.57 centimeter) than the General Electric ring (1.34 centimeter). Data were presented showing that Kurz's ring was clearly resonant at 9.05 GHz with an attenuation of > 50 decibel. The fact that the attenuation fell to ~ 20 decibel at 8.5 and 9.6 GHz indicates one reason why more than one resonant ring was used. Quoted values of wow were < 1.02. Insertion loss was under 0.1 decibel.

2. Waveguide Rotary Joints Using the H_{11} Mode in Circular Waveguide

We have discussed the operation of rotary joints using the E_{01} mode in circular waveguide. It is possible also to utilize the fundamental mode in circular waveguide, namely, the H_{11} mode. This admittedly does not have circular symmetry, but can be given a pseudo-circular symmetry by circularly polarizing it for propagation across the rotor-stator interface. This is accomplished in the manner described below.

A rectangular waveguide feeds microwave energy via a transition into circular waveguide of diameter such that only the H_{11} mode can be propagated (λ_c = 1.705 D). Since the E_{01} mode can be propagated at wavelengths below 1.305 D, λ should lie between λ_c and 0.77 λ_c.

The polar H_{11} mode energy is then incident at 45 degrees on a quarter-wave plate and emerges circularly polarized. It makes the transition across the stator-rotor interface; in the rotor section, an identical quarter-wave plate and transition to rectangular waveguide exist. However, since the circular-to-rectangular transition represents a short-circuit for H_{11} signals with a plane of polarization at 90 degrees to the E-direction of the rectangular guide, these are reflected. Such signals result from imperfectly circularly polarized signals since perfectly circularly-polarized signals are impossible to accomplish over a frequency band of any magnitude. The consequence is that these unwanted signals are reflected back and forth between the two end transitions and, for certain lengths of the circular waveguide, resonances are set up. The effective length of the guide also varies on rotation so that the conditions for resonance (equivalent electrical length equals an integral number of half-guide wavelengths) are satisfied at certain angular positions of the rotary joint.

Resonance problems can be greatly reduced if the circular waveguide "looks" at both ends into two rectangular waveguide transitions which between them accept any plane of polarization of incident energy without appreciable reflection (Figure 4). Matched loads adsorb the energy received in the rectangular guides which are not connected either to transmitter/receiver or antenna. This arrangement is also capable of dual-channel operation with each channel corresponding to one plane of polarization at 90 degrees to the other channel. This will be described in more detail later, when considering multichannel rotary joints.

Rotary joints using circular polarization have been described.[8,9,10] They are usable only as narrow-band components if no attempt is made to solve the resonance problem. That is, they are used only at frequencies away from resonance frequencies. However, resonant adsorbing slots in the walls of the circular waveguide can be used to suppress unwanted resonances. They function as radiating slots and couple strongly to the orthogonal mode, but not to the mode of interest.

Dielectric plates are primarily used as the quarter-wave plate material; they should be free from surface contamination, as this frequently reduces the power-carrying capability of the guide. An alternative to transmitting the circularly-polarized energy across the

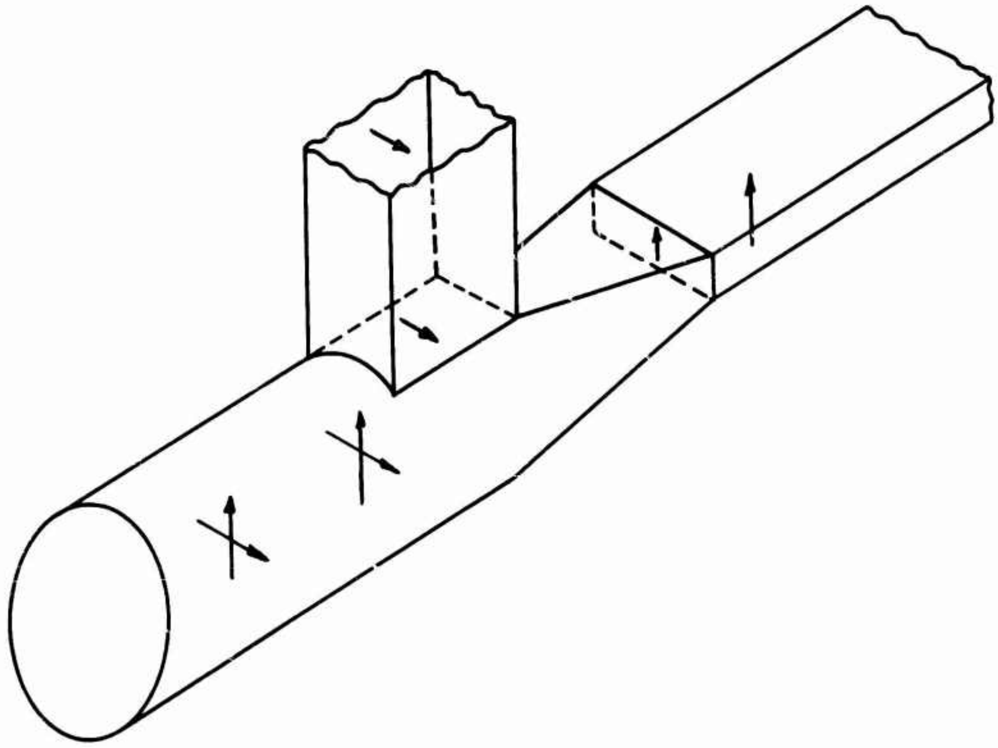


Figure 4. Rectangular-Circular Waveguide Transition for Propagating Two Mutually Perpendicular H_{11} Modes in Circular Waveguide

stator-rotor interface is to use circular horns instead of circular waveguide.[10] However, there is no reason to believe that resonance problems are absent here. It should be explained that the electrical length of a rotary joint, using circular polarization, varies as the joint is rotated.

The function of the two quarter-wave plates combined is essentially to rotate the plane of polarization of the H_{11} mode in the circular waveguide. This can be accomplished alternatively using ferrite devices.[11, 12] Faraday rotation of the plane of polarization of the H_{11} mode occurs and depends on the length of a matched ferrite rod supported along the cylindrical axis of the waveguide and also on the direction of an externally applied dc magnetic field perpendicular to the cylindrical axis. The means are provided whereby the external magnetic field applied is rotated with the rotor; the means can be either a magnet or a magnetic coil. It is also necessary to vary the magnitude of the magnetic field, and this is accomplished either by a controlled variation of coil current or by a cam controlling the separation of the permanent magnet from the ferrite. Specific performance data are lacking on these rotary joints.

3. Waveguide-Coaxial Line Rotary Joints

Waveguide-coaxial line rotary joints consist of a coaxial line-to-rectangular waveguide transition at both ends of a section of coaxial line. At least one transition must be symmetrical about the coaxial-center conductor to permit its rotation. The principal coaxial mode is always used, and the line is operated below cutoff for all higher modes. Waveguide-coaxial line transitions are either L-shaped or in-line depending upon how the transition affects the direction of energy flow. Different combinations of these transitions account for in-line (I), L- or U-types of rotary joint.

It is appropriate, therefore, to consider various types of waveguide-to-coaxial line transitions.[13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29] In general, these involve the coaxial line entering the waveguide either on the broad face or on the end face (in-line transition). In terms of bandwidth and power-handling capability, the doorknob transition is undoubtedly the best transition. Modern designs have departed from the original doorknob shape for the termination of the coaxial-center conductor; this is now usually a truncated cone with a cone semi-angle around 36 degrees. It is also usual for the matching piston to have a semicircular shape as this increases the bandwidth of the transition. Another advantage of the doorknob transition follows, since the

coaxial-center conductor can be hollow, terminating as it does on the truncated cone. This hollow channel can be extended right through the cone, and one or more extra coaxial channels can pass through the rotary joint in this manner.

Other broad face of L-transitions are the probe transition and the cross-bar transition such as are described in Volume 9 of the MIT series mentioned in the Introduction. The coaxial-center conductor is usually rounded off where it terminates inside the rectangular waveguide in order to reduce the chances of voltage breakdown at the tip. This does not have any significant effect on the match. The crossbar transition is a rather broad-band coaxial line-waveguide transition with reasonable power-handling capabilities; however, since it is not circularly symmetrical about the coaxial-center conductor, it can only be used as the fixed end of a waveguide-coaxial line rotary joint. Some other design must be used for the transition in the other half of the joint.

Normally, the coaxial line is air-filled. This means that in the case of the probe transition, some means must be found to support the center conductor and half-wave dielectric plugs are used for this purpose. This reduces the power-handling capability of the line by approximately four factors. An all-dielectric line, using teflon, can be constructed which has equally good power-handling capability as an air-filled line providing no air-gaps are allowed inside the teflon, particularly at the rotor-stator interface at the center conductor. Teflon has a low coefficient of friction, and rotor and stator dielectric teflon parts simply slide over each other. At the transitions, from waveguide to coaxial line, the dielectric extends across the guide to the opposite broad face.

In-line transitions generally are slightly inferior to L-transitions when comparing power-handling abilities. However, where large amounts of continous-wave power are carried and heat dissipation aspects are important, the in-line transitions have better characteristics since the center-coaxial conductor is connected to the broad face of the waveguide which forms a good heat sink.

Also, a note may be made here of a waveguide-coaxial line transition which is called a double waveguide-coaxial transition.[14, 28, 29] The input waveguide feed first splits into two waveguide sections (Figure 5) which are bent to form two halves of a ring. At the point when they meet again diametrically opposite the waveguide feed input, the transition to a coaxial line takes place. The advantages claimed for this design are good broadband performance (20 percent), and larger

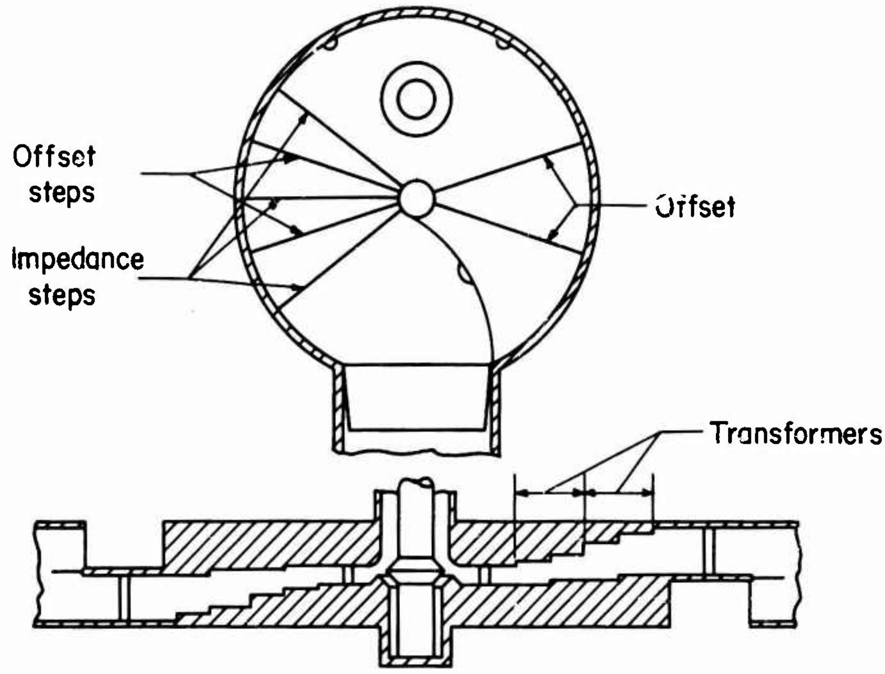


Figure 5. Double Waveguide-Coaxial Line Transition

diameters of coaxial line are possible in order to handle higher powers without encountering difficulty from the presence of the H_{11} mode which is theoretically propagable, but is not excited by the transition. The limiting mode for the coaxial line is the H_{21} mode.

4. Waveguide Mode Convertor Rotary Joints

Some waveguide rotary joints, which are characterized by a multiple splitting of the microwave energy input before recombining it in various suitable forms for passage from stationary to rotating parts of the joint, have been described. Once in the rotating section, the signal makes the passage back to rectangular guide by a process of feed recombination which is the reverse of the feed-splitting process. These joints are distinguished in that the design permits a large hole in the center of the joint through which feeds for other channels can pass.

Smith and Mongold[30] described such a C-band joint in which the input power was divided 15 times by double corners. The cross section of the 16 waveguide channels is then changed by slightly flaring one

E-dimension of each guide to form a keystone segment as shown in Figure 6. The E-dimensions gradually change into arcs of a common circle. The 16 feeds are then so disposed to form 16 segments of a circle and thus the power emerging from these feeds is in a H_{01} coaxial mode when the radial-conductive walls are removed. The larger E-dimension of each keystone is less than $^1/_2$ λ_c and so prevents the excitation of higher modes. The common exit plane of the waveguide feeds form the rotor-stator interface plane. The power passes across a small gap to an identical rotating section and recombines in the inverse sequence to a rectangular H_{10} output. No radio frequency leakage at the gap occurs because the electrical fields are closed in the coaxial H_{01} mode existing at the interface. No longitudinal currents flow across the gap and because of this, choke joints are not required.

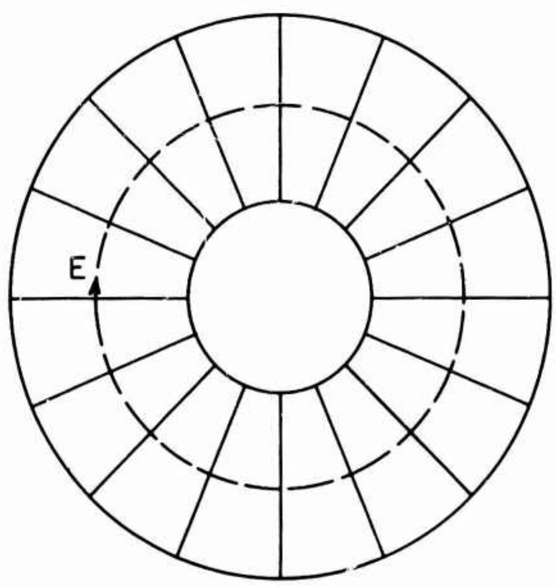


Figure 6. Sixteen Keystone Waveguide Cross-Sections Assembled to Force the H_{01} Coaxial Mode

A 10-percent bandwidth for a VSWR < 1.15 was achieved for this design with negligible wow. Insertion loss was slightly in excess (0.07 decibel) of the theoretical insertion loss expected for a straight section of waveguide of the same electrical length. Peak powers of 3 milliwatt at C-band across the 10-percent band were handled without breakdown when the input feed was pressurized. Breakdown is not a problem in the joint itself since each waveguide segment is handling only one sixteenth of the total input power.

A similar joint utilizing eight waveguide feeds has been described[31] with a claimed 30-percent bandwidth. Moding problems arise with this number of feeds and unwanted modes are filtered out with a series of lossy chokes. This type of joint requires extreme care in making, since the 8 to 16 different paths to the rotor-stator interface must be equally long electrically within very close limits. In addition, the matching of the joint with so many different sources of mismatch present is tedious and difficult to achieve.

5. Waveguide Annular Rotary Joints

A number of designs have been described which have as a common feature, a waveguide section forming the circumference of a ring or annulus. In consequence of this, the possibility exists of running other channels in waveguide or coaxial line through the central hole of the annulus. These designs are somewhat complex; they have the disadvantage of having resonance problems at certain frequencies, a variable electrical length as the joint rotates and somewhat high insertion losses.

The annular rotary joint described by Breetz[32,33] consists of a ring waveguide bent in the E-plane and with input and output feeds to the ring on opposite sides of the ring. They are mobile relative to one another since the waveguide is split at the edges of the inside face of the ring guide to form rotor and stator parts. Since this corner is a region of high current flow, half-wave chokes are required. Attached by the feed arms where they enter the ring, are sets of metal fingers which extend across the width of the guide at an angle to function essentially as a waveguide bend. The fingers located at input and output are interdigitated with respect to each other in order to permit continuous 360-degree rotation of the joint. Six and five fingers were used, respectively. The chokes were made to bend with the ring guide so that the chokes had the same curvature as the bent guide in order to allow the exciting waves of the waveguide to have the same phase relationship as the excited waves in the chokes.

In the crossover position (Figure 7) and also in any general position, power flows from the input to the output by a path around the ring whose electrical length varies with the position of rotation. However, when the arms are in positions very near to crossover, the fingers act as power dividers. The mean circumference of the ring is such that the path lengths P_1 to P_4 and P_5 to P_6 (Figure 7) differ by an integral number of guide wavelengths for the center operating frequency. Since the ring is normally several guide wavelengths in circumference, a small

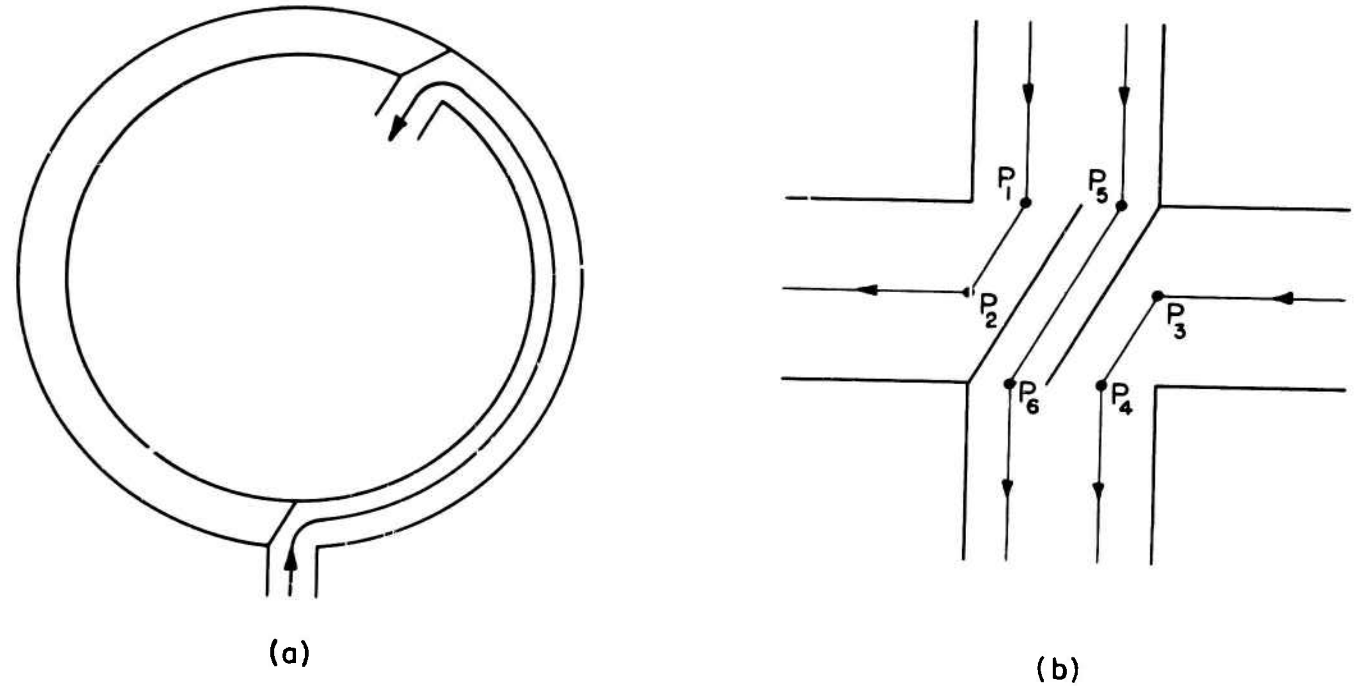


Figure 7. Cross-Sectional View of Ring Waveguide Rotary Joint Illustrating
(a) Electrical Paths in Non-Crossover Positions
(b) Electrical Paths in Crossover Position

change in frequency will make the path difference depart from integral wavelength values and the joint mismatch increases greatly. Then the joint is characterized by a number of narrow, evenly spaced pass bands corresponding to a low VSWR in the critical crossover region. At a non-crossover position, band-pass problems do not exist except those introduced by the chokes and finger bends.

The Tomiyasu design[34, 35, 36] of annular rotary joint and also the Boronski design to be considered later, utilize waveguide couplers for the transfer of microwave energy from the stationary to the rotating elements. The Tomiyasu design utilizes two waveguide rings bent in the E-plane and with contacting narrow walls since they rest one on the other. Input and output feeds are on opposing sides of the double ring. Electromagnetic coupling between the rings is accomplished by a series of closely-spaced identical apertures along the common waveguide wall. The total length of the coupling section for 100-percent power transfer at X-band in WR 90 is about 8-$^1/_4$ inches. The degree of coupling for other lengths of coupling follows a sine-squared law. The apertures, 22 in all, were defined by 21 wires of 0.04-inch diameter, 0.4-inch long and spaced $^3/_8$-inch between centers. On the waveguide wall opposite the coupling element, an insert is soldered to compensate for the missing waveguide wall, otherwise, 100-percent power transfer does not take place. The ring with the outer terminal has on one narrow wall an opened section 225 degrees long. The ring into the inner terminal has two 90-degree long couplers spaced about 45 degrees apart.

The coupling elements are so arranged that, when one is coupling 100 percent, the other is shuttered off. In positions when one is partly shuttered so that less than 100-percent power is coupled, the second coupling element is partly unshuttered by the correct amount so that between them, 100-percent power is coupled to the output feed. Another possibility occurs when one coupler is completely unshuttered and the other is partly unshuttered. This also results in 100-percent power transfer and corresponds to the "diagonal arm" condition of any coupler, wherein, if a pair of diagonally opposite arms are connected so that one feeds into the other, 100-percent power transfer takes place between the other two arms, regardless of the electrical length of the connection between the two connected diagonal arms. Thus, 100-percent coupling occurs throughout the full 360 degrees of rotation and no dead spots are found. At the point when the input ring has an open narrow wall in contact with the output ring, relative motion between these surfaces takes place, and a choke is necessary at this point.

In order to preserve the guide wavelength within the opened section of the outer terminal ring, it is necessary to maintain the guide width

constant by soldering an additional metal insert against the opposite narrow wall to attain 100-percent power transfer.

Good match and low insertion loss is found only in certain very narrow pass bands. At other frequencies, resonance effects occur at certain rotational positions and insertion losses up to 50 decibel result. The joint is capable of handling high power; no problems of breakdown were noted when handling 210 kilowatts at 9.375 GHz, a frequency at which problems of resonance are absent.

The Boronski design[37] uses three E-plane waveguide rings which are concentrically stacked. The lowest ring couples the input power into the middle ring by means of multiple narrow-wall slots which are about one quarter guide wavelength long and spaced apart by about the same distance. These slots extend about 300 degrees around this middle ring. The middle ring is separated down the center of the broad faces, and this forms the rotor-stator interface. This being an electrically neutral axis, chokes are not needed to electrically bridge the physical break. The power is then coupled by an identical coupler design into the third waveguide ring. Matched loads are incorporated into the two outer rings.

So far as the design of coupler is concerned, a single row of identical slots was found to have good power-handling capabilities. A double row of thinner slots presented a lower mismatch, but had inferior power-handling capabilities. The transmission characteristic of the rotary joint, as a function of frequency, has a succession of pass and stop bands, the number of these depending on the diameter of the joint for a given operational bandwidth. As in all annular designs, this is due to the center ring acting as a traveling wave resonator. When the circumference of this ring equals an extra half wavelength, a wave traveling around the ring arrives back with 180-degree phase difference, and the output power is dependent on the angle of rotation. When input and output ports cover each other, there is zero output, the incident power being reflected from the middle ring and adsorbed in the input ring load. However, in any other position, some power is transmitted, reaching a maximum in the 180-degree position. Boronski terms those frequencies where this behavior occurs "stop-frequencies". The insertion loss over two thirds of the band between adjacent stop frequencies is under 1 decibel. Due to the presence of the coupling slots in the center waveguide, the guide wavelength would normally decrease. Since it is important that the guide wavelength in all three rings be approximately equal, the broad dimension of the center ring is decreased by about six percent to achieve this.

A variation of the Breetz method of annular operation has been described.[38] Whereas Breetz used fingers extending across the guide at 45 degrees to accomplish the flow of energy in the desired direction, this directivity was alternatively accomplished by either two resonant half-wave slots in the form of a cross in the broad face of the annular waveguide or a combination of two hybrid T's in the rotor section and an E-plane bend in the stator section. Crossover problems exist as in the case of the Breetz design; however, the design handled higher power since the resonant-crossed slots were filled with a suitable dielectric.

The Bouix annular joint[39] made use of H-plane corners feeding in and out of a waveguide ring bent in the E-plane. The directivity of the H-plane corners was controlled by two metal plates which could enter or leave the waveguide at a predetermined distance from the waveguide feed. With one plunger effectively short-circuiting the waveguide, the power flows away from the plunger around the annulus, providing the other plunger was out. The same arrangement prevailed at the exit feed and as the joint rotated, these plungers automatically moved in or out of the waveguide at the appropriate moment.

An annular design similar to Boronski's design[40] utilizes slots to couple power from an input waveguide to a resonant circular ring and thence, via further slots to the output waveguide. Due to a helical configuration of the various waveguides, the center waveguide is coupled completely to input and output waveguides for all angular positions of the joint.

Another variation[41] on the theme of coupling an input stationary waveguide via an intermediate member to a rotating output member apparently originated from an antenna design. The coupling slots on the input waveguide are inclined slots at calculated angles on the narrow face so that, in open space, they would function as radiating dipoles. However, this annular waveguide and a corresponding slotted output waveguide are held between metal sheets. The distance between waveguides is so large that power virtually passes in a radial direction from one waveguide to the other. This is assisted by vertical plates having a semihorn function in the intervening space.

6. Coaxial Rotary Joints

Recently, very little has been written about purely-coaxial rotary joints, indicating that optimum design approaches are well established. Some six patents[42,43,44,45,46,47] have been issued since 1951; it is not evident from data presented whether they are capable of

operation at S-, C-, or X-bands. One[46] incorporates a tunable choke; yet another[47] is concerned with sliding contacts of coin silver on a silver-graphite composition so that the joint can be used from dc up to into the microwave region. A joint made by Diamond Antenna and Microwave Corporation using this contact principle is claimed to be usable with VSWR < 1.5 from dc to 16 GHz. A broad-band joint using capacitive coupling instead of chokes has also been described.[48, 49] The VSWR is < 1.5 from 0.1 to 12.4 GHz, and the joint safely handles 20 kilowatts of power. Although the coaxial dimensions were such that a high mode was propagable above 19 GHz, this did not appear, at least below 12.4 GHz.

7. Multichannel Rotary Joints

In certain applications, rotary joints are required to handle a multiplicity of channels. Some approaches to this problem are as follows:

1) For dual channel joints, designs involving the propagation of two circularly polarized waves or of two different symmetrical modes in circular waveguide have been reported.
2) Multicoaxial line rotary joints in which the inner conductor of one coaxial line serves also as the outer conductor of another coaxial channel. Several channels can be accommodated in this way.
3) "Around-the-mast" joints which are stackable and provide a large hole in the center of the joint through which feeds to other stacked joints can pass.

These three methods will be considered in the foregoing order.

a. Dual Channel Rotary Joints Using Circular Waveguide

It is a well-known art to propagate circularly-polarized waves in a circular waveguide. If one provides two rectangular feeds to the circular waveguide (Figure 4) so that the plane of polarization of the second feed in the circular waveguide is at 90 degrees to the plane of polarization of the first feed, then on passing through the quarter-wave plate structure, two circular polarizations of opposite senses result. If the break between rotating and stationary members is made in the section of circular waveguide through which circularly-polarized waves are propagated, the waves then become plane polarized on further passage through a quarter-wave plate and leave the circular waveguide

by one of two rectangular waveguide outputs appropriate to the plane of polarization. Isolation between the two channels is dependent on the perfection of circular polarization achieved. Metal stubs, plates, or dielectric slabs can be used as the quarter-wave plate element.[50,51,52] Isolation greater than 50 decibels over a bandwidth of 11 percent is possible.[52]

Another method[53,54] of propagating two channels in a circular waveguide uses two different modes of propagation to achieve channel isolation. These modes are the E_{01} mode previously used for single-channel rotary joints and the H_{01} mode. Both these modes have circular symmetry. Since the E_{01} mode produces a longitudinal current, electrical continuity across the break at the rotor-stator interface is achieved by means of a choke.

For good isolation between channels, the input and output feeds for each channel should excite a pure mode in the circular waveguide. It will be recalled that the cutoff wavelength for the E_{01} mode in circular waveguide is 1.305 D; for the H_{01}, it is 0.82 D with the next higher mode, H_{31}, coming in at 0.75 D. Two other modes, H_{21} and E_{11}, are possible between E_{01} and H_{01}. The E_{01} mode is excited by a coaxial coupling rod extending from a waveguide feed into the circular waveguide through a hole in the end plate and lying along the cylindrical axis.

The H_{01} mode is excited by four resonant slots centered one quarter-guide wavelength from the end plates and equally spaced around the guide. The distance from input to output slots should be an integral number of half-guide wavelengths. Since the currents feeding the slots have to be equal in amplitude and phase, the waveguide feeding the slots is designed so that the slots are an integral number of wavelengths apart. This is achieved by the waveguide-ring feed shown in Figure 8. The microwave energy is divided into two paths at the T-junction. For good match, the triangular prism has to be properly dimensioned, and the ring waveguide has to be half the narrow dimension of the feeding waveguide.

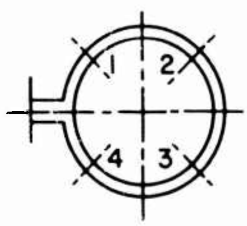


Figure 8. Scheme of a Transition from Rectangular H_{10} Mode to Circular H_{01} Mode

This joint is a narrow band design; the VSWR is ≤ 1.5 over a 0.7 percent frequency band for the E_{01} channel and over a 1.3-percent frequency band for the H_{01} channel. Electrical lengths of the joint can vary slightly for the E_{01} channel due to mechanical imperfections. Cross talk or isolation between channels varied with angle of rotation; it was always greater than 42 decibels.

b. Multicoaxial Line Rotary Joints

Reference has already been made to the fact that, in rotary joints employing coaxial lines at the rotor-stator interface, a multichannel capability exists for passing further channels through the joint by making hollow the center conductor of the coaxial line. Figure 9 illustrates this principle in making a three-channel rotary joint, using a doorknob transition. Such multichannel joints can have waveguide feeds or be all-coaxial. Clearly, there is a limit to the number of coaxial channels which can be accommodated in this way, seven may be an optimistic limit. Exactly what can be accomplished in this way depends on the power and frequency at which each channel must operate. As the dimensions of the inner-coaxial lines become smaller and smaller, so does their power-carrying capacity. Normally, one has to consider avoiding coaxial dimensions permitting the propagation of modes other than fundamental. Then the larger, outer-coaxial line(s) are arranged to carry the lowest frequencies.

The feeds to this type of joint can be coaxial as well as of rectangular waveguide. The principles of purely-coaxial rotary joints are well established and the problems are usually one of designing the joint to satisfy the requirements of size, bandwidth and power-handling. Extensive use is made of T-stubs in the coaxial line where many channels are to be accommodated. Various multichannel rotary joints incorporating these principles have been described.[55,56,57,58,59,60]

A dual-channel rotary joint has been described[61] which is based on the use of a single coaxial line. This joint is operable only when the frequencies in each channel differ by a factor of 3:1 or more. Briefly, the high-frequency channel consists of a rather conventional waveguide-coaxial line waveguide rotary joint. However, the center conductor is not connected physically in the transition to the broad waveguide face but used chokes to make the electrical connection. The second frequency is then introduced from behind the waveguide-coaxial line transition and is of a frequency such that the chokes represent an open circuit across the line to this signal. Consequently, this signal can pass into and out of the center-coaxial section. Therefore, use has

been made of the frequency-sensitive properties of a choke so that it acts as a filter. Because of this, the device is not a broad-band device. The second channel can be introduced either from a larger waveguide corresponding to the lower frequency or have a simple coaxial input.

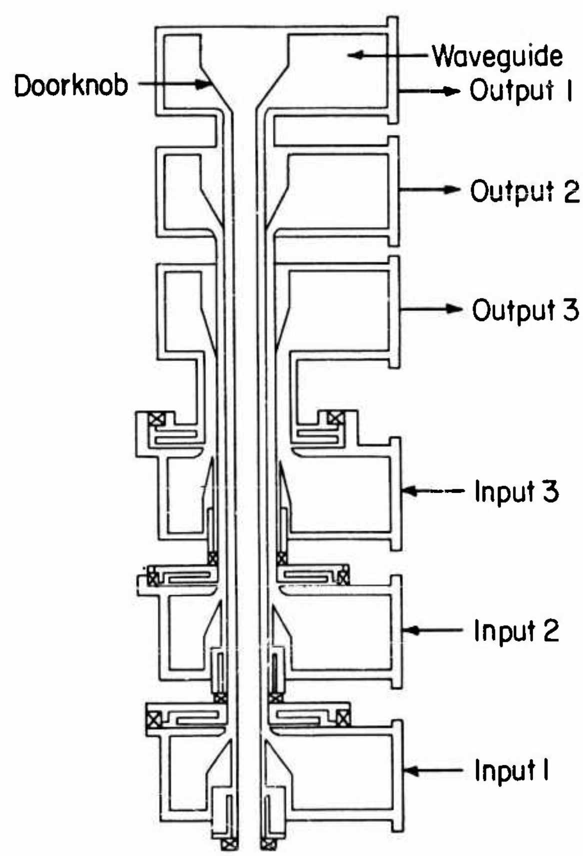


Figure 9. Cascaded Doorknob Transition Joints

c. "Around-the-Mast" Rotary Joints

Much of the interest in the annular and ring types of rotary joint, which admittedly are more complex and expensive than simple single channel joints with either round waveguide or a coaxial line, arises because of their ability to be stacked one above the other around a stationary structure such as a mast. A necessary condition for this is that the rotary joint has a sufficiently large central hole in it to permit the mast and microwave feeds to other joints stacked above it to pass through it. Because of this, one is often willing to pay the penalty of using a joint which is unusable at certain resonant frequencies which are avoidable. As previously defined, annular designs of rotor joint possess this suitable central hole and can be stacked one above the other. Other rotary joints with a large central hole are the pancake and neutral-plane feed rotary joints.[31, 62, 63, 64, 65, 66, 67]

The pancake joint consists of a short coaxial joint with the center conductor large enough to permit the large central hole; in consequence, high modes can be propagated along the coaxial line. The feed system forces the fundamental coaxial mode by feeding the oversized coaxial line with four or eight symmetrically placed probes excited by fields of equal amplitude and phase (Figure 10). This is accomplished, as in the case of the mode-converter waveguide joint, by equally dividing the power a number of times into electrically equivalent channels. In the case under discussion, the division was accomplished by a stripline network. One ingenious aspect of this short joint is that no break need be made in the center conductor, but one is located in the associated choke section. This is useful for improving the mechanical rigidity of the joint.

At high powers, the presence of even small amounts of higher modes in the coaxial cavity can cause arcing between rotor and stator. To avoid this, mode filters (longitudinal slots containing a lossy material) are incorporated in the outer conductor. These have little effect on the fundamental coaxial mode.

In the megawatt region, solid dielectrics cannot be used without breakdown problems to support the feeds. This is accomplished by quarter-wave stubs appropriately placed. As many as 15 joints of this type have been stacked together at S-band. Powers of 2-$^1/_2$ milliwatts can be handled at S-band. Bandwidth is at least 12 percent.

The neutral-plane feed system as shown in Figure 11 is a mechanically simplified pancake joint in which part of the strip feed functions

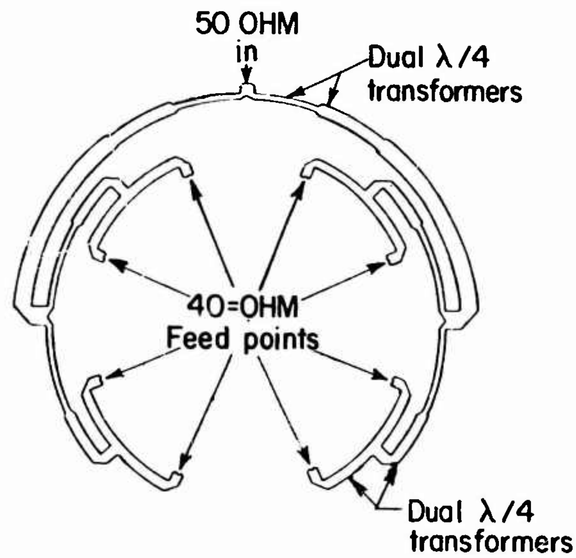


Figure 10. Stripline Feed System for Pancake and Neutral Plane Feed Rotary Joints

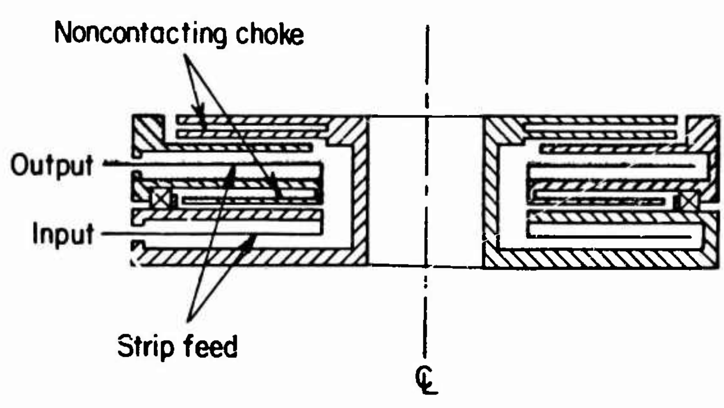
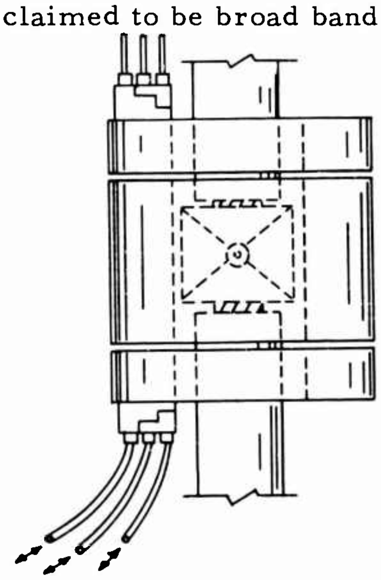


Figure 11. Transverse Cross-Sectional View of Neutral Plane Feed Rotary Joint

as a quarter-wave choke. With one quarter-wave choke in each half of the joint, the joint becomes a half-wave cavity which is excited by connecting the strip feed system to one of the ground planes at or near the center of the joint. The feed system functions as a coupling loop. This joint has a doubled bandwidth and can handle as much power as the pancake joint.

Similar coaxial cavity joints which handle a mere fraction of this power have also been described;[31, 68] the power-handling capability is smaller because the coaxial line is fed at only one point--no power splitting is involved--and the line is kept small enough that no higher mode can be propagated in the line. Furthermore, the central hole is smaller, so that relatively miniature feed cables must be used to pass through the central hole if several channels are required.

A multichannel rotary joint of novel concept has been described by Bowman.[69] This embodies an input stator section, containing one or more feed horns, a center section containing a multiplicity of waveguides and which rotates at half the rate of the rotor output section, this being of similar construction to the input (Figure 12). A view of the center drum configuration is given in Figure 13. Each horn feeds more than one waveguide. Every waveguide joining top and bottom positions on this drum is arranged to have the same electrical length. Such a joint is claimed to be broad band and high power.



Note: The Lower Drum is Stationary and the Upper Drum Must Rotate at Twice the Rotational Rate of the Center Drum.

Figure 12. Multichannel Rotary Joint Arranged Around a Mast

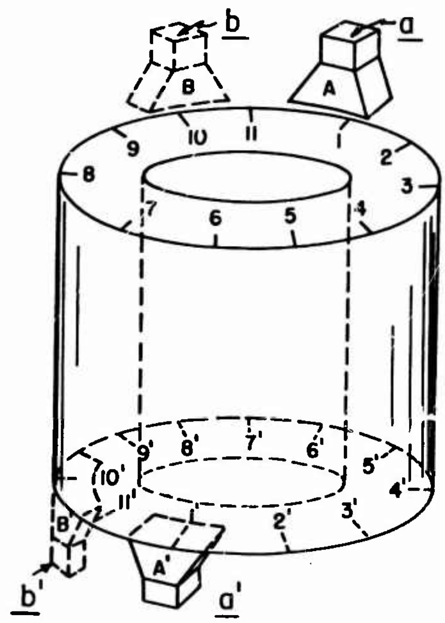


Figure 13. How Input and Output Waveguide Horns Are Mutually Arranged with Respect to the Center Drum of Figure 11

Section III. CONCLUSIONS

Having described in detail the microwave rotary joint designs for X-, C-, and S-bands, it is appropriate in conclusion to add some perspective to the information presented.

It is the author's impression that the field generally is somewhat static. This situation indicates that engineers are generally satisfied with those joints which are commercially available. Where the available joints are inadequate, it is quite usual to make an in-house design of rotary joint for the particular application.

So far as single-channel joints are concerned, purely coaxial and waveguide-coaxial line joints predominate, but joints embodying circular waveguide also have sufficient supporters.

These joints have an almost constant electrical length as the joint rotates; however, joints embodying the propagation of a circularly-polarized wave in circular waveguide have a variable electrical length as the joint rotates. This is also true of dual-channel rotary joints which propagate two circularly-polarized waves in circular waveguide.

For multichannel applications, the pancake joint and its variant, the neutral-plane feed joint, seem to have advantages for applications where many joints must be stacked one above the other. Fifteen such standard joints have been described. Waveguide mode convertor and annular designs are so much more expensive, bulky, and complex that they are in practice considered for multichannel operation only when absolutely necessary. The waveguide-mode convertor design has the highest power-handling capability of all joints considered. The annular designs have the disadvantage of variable electrical length as the joint rotates, and also resonance problems.

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13. ABSTRACT

This report consists of an examination of post-1950 rotary joint designs for use at X-, C-, and S-bands. Among the topics discussed are single and multichannel rotary joints with coaxial line or rectangular waveguide inputs. Since the simplest waveguide rotary joints incorporate transitions from rectangular to circular waveguide or from rectangular waveguide to a coaxial line, calculations are included on the relative power-handling capabilities of circular waveguide, rectangular waveguide, and coaxial line when subject to the conditions necessary for prope[illegible]tioning of a rotary joint.

A detailed examination is made of rectangular waveguide joints of the coaxial line, circular waveguide, coaxial mode convertor, and of the annular varieties. It is shown that, in the circular waveguide variety, either a circularly polarized H_{11} mode or an E_{01} mode can be used. Methods of avoiding undesirable performance due to resonances in the circular waveguide are discussed. Methods are described of using circular waveguide rotary joints for dual-channel applications.

Rotary joints, incorporating a section of coaxial line, are discussed; it is shown that, for "around-the-mast" applications, by employing special feeds to the coaxial section, coaxial-line dimensions can be increased without appreciably exciting higher, undesirable modes which could in theory propagate. A brief discussion is also made of purely-coaxial rotary joints.

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13. ABSTRACT

The more complicated mode convertor and annular-rotary joint designs are described, and it is indicated that, like certain waveguide rotary joints incorporating a coaxial line section, their chief merit lies in their possibility of use for "around-the-mast" applications.